The logistic design of the LOFAR radio telescope

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Chapter 3

The LOFAR Project

3.1 Introduction

The *LOFAR project* is a unique ICT project to build the world's largest radio telescope. The so-called LOFAR telescope will operate at the lowest radio frequencies accessible from earth to explore the universe from its early beginnings (ASTRON, 2007b). It also provides a fast ICT infrastructure that will be accessible for people from other disciplines (e.g., geophysics and agriculture) and gives stimuli to the socio-economic environment (Bsik/LOFAR Consortium, 2003).

The outline of this chapter is as follows. Section 3.2 discusses the consortium in which the LOFAR project has been developed. Then, in Section 3.3 we explain the scientific, technological, and socio-economic motivations of the research project. After that, Section 3.4 gives a description of the basic architecture of the telescope. Finally, Section 3.5 explains the site selection process of the LOFAR telescope.

3.2 LOFAR Consortium

The LOFAR project has been developed in a consortium of knowledge institutes, universities and industrial parties (Bsik/LOFAR Consortium, 2003), whose main objective is to set up an infrastructure enabling modern ICT research and new applications so that new knowledge is effectively exchanged. Intellectual property has been the main driver of the LOFAR project. The groups that have led the efforts are ASTRON, Haystack Observatory at MIT, and the US Naval Research Lab. For the second phase of the program – the actual construction of LOFAR – a new consortium has been formed with ASTRON as its leader.

ASTRON is the Netherlands Foundation for Research in Astronomy. It was founded under Dutch law in 1949 as the foundation for radio radiation from the sun and the Milky Way. It was charged with the development and operation of radio telescopes. In 1949, ASTRON had 20 employees (ASTRON, 2007a).

At present, ASTRON has over 200 employees. Its core mission has changed into enabling astronomical discoveries. The strategy of ASTRON to meet the mission statement is to provide innovative instrumentation for the astronomical community that is suitable for a wide range of frequencies and techniques. The strategy will be implemented by the development of new, innovative instrumentation for existing telescopes and new technologies for future observation facilities. ASTRON will participate in the international arena to establish cooperations with international organizations in order to achieve its goals (ASTRON, 2007a).

3.3 Motivation behind the LOFAR Project

The main purpose of the LOFAR project is to build a radio telescope that enables new discoveries in astrophysics and space physics. The LOFAR project is also a cross-disciplinary research program since it provides opportunities for a wide range of disciplines. The cross-disciplinary nature of the LOFAR project is given in Bsik/LOFAR Consortium (2003) by the following three aims of the research program:

- cooperation across research communities to add value to each of them;
- innovation in research; and
- development of a unique infrastructure to support that research.

In the remainder of this section we give an overview of the opportunities of the LOFAR research program. We make a distinction between scientific opportunities, technological opportunities, and socio-economic opportunities.

3.3.1 Scientific Issues

The science case of the LOFAR project is described in Van Haarlem (2002, 2003). These reports outline the areas of science to be addressed by the LOFAR project. The scientific issues of the LOFAR project are discussed in the LOFAR core objectives and the non-astronomical objectives.

LOFAR Core Objectives

The LOFAR core objectives are objectives related to astrophysics and space physics that are considered as most important. These objectives are listed below:

- The Epoch of Re-ionization (EOR): the detection and mapping of global signals from the period of re-ionization (see Section 1.1).
- Extragalactic science (EXG): the study of the extragalactic radio sky, and in particular, the study of the *high redshift universe* (see glossary, p. 259).
- Galactic science (GAL): the study of the distribution of ionized hydrogen atoms throughout the Milky Way galaxy and the origin of cosmic rays emitted from the Milky Way.

- The bursting and transient universe (TRANS): the detection of short-lived transient events in the universe.

- Solar-terrestrial science (SOL): the detection of *coronal mass ejections* (see glossary, p. 259) from the ground possibly in combination with a solar radar.

Non-Astronomical Objectives

LOFAR is a ground-based telescope, so its performance depends on the atmospheric conditions. Due to the opaqueness of the ionosphere and *radio frequency interference* (RFI; see glossary, p. 259), it is difficult to observe cosmic radiation at low frequencies. Ionospheric irregularities further complicate radio observations. Besides, the local weather conditions and the space weather physics also affect the performance of LOFAR. These problems should be studied in the field of atmospheric science.

The LOFAR antenna systems will also be equipped with geophones and seismometers (De Vos, 2004). These sensor devices are used to obtain insights in the subsurface of Northern Netherlands. Geophysical research will focus on the impact of extracting gas from the natural gas reservoirs on ground subsidence and seismic activity in Northern Netherlands.

The LOFAR research infrastructure will also be used for the agricultural science, especially in the area of *precision agriculture*. Precision agriculture is a research area that increases in importance due to the declination of European subsidies in agriculture. A proposal has been submitted by the Dutch agriculture community to establish dense local-area networks of soil and weather sensors close to the antenna systems of LOFAR.

3.3.2 Technology Issues

There are many technology issues related to the LOFAR project. Some of these issues are listed in Bezemer and De Jong (2003), which are explained below.

LOFAR requires a large number of receptor elements and computer systems. The receptor elements have been built such that they can operate in the LOFAR frequency range (see Section 3.4). Computers have been designed and constructed to process the huge amounts of data observed from the universe, to extract valuable information from it, to compress this information, and to store it. Furthermore, software has been developed to control the telescope, to calibrate and process the data, and to make the data available for users. Finally, technologies are developed for the construction and maintenance of the antenna systems and the transmission network.

The launching customer of the LOFAR research infrastructure still needs to be determined. A tender call should give network providers the opportunity to build the research infrastructure and to exploit the network for the commercialization of new high-capacity demanding ICT applications (SURFnet, 2005). The fiber optic network linking up the LOFAR antenna systems will offer data transfer rates of at least ten gigabits per second (De Vos, 2004) making these ICT applications possible. The following ICT applications have received much attention (Bentum, 2002):

- video phone;
- video mail;
- video on demand; and
- online filing.

Wireless communication has experienced a rapid development in the last ten years. The new generation of wireless techniques (WLAN) and mobile networks (UMTS) make it now possible to create ICT applications for wireless communication in the home situation and the industry sector, but also for usage on the way. Wireless applications can only be realized if the UMTS stations of the mobile networks are linked up to a high-capacity ICT network. The LOFAR research infrastructure provides such a network allowing these wireless applications to be developed.

3.3.3 Socio-Economic Issues

Several studies have been performed to determine the socio-economic relevance of the LOFAR project. The next discussion of possible socio-economic effects is based on Bentum (2002), Van der Horst (2002), and Bezemer and De Jong (2003). The LOFAR project has direct and indirect employment effects. Direct employment is generated by the laying, exploitation, and maintenance of the LOFAR cable infrastructure, and by the development and production of hardware and software. Indirect employment is generated by the spinoff of knowledge, the development of new ICT applications, and the demand for a servicing and supplying industry. Table 3.1 shows an overview of the expected employment effects of the LOFAR project. It shows the average number of (extra) job vacancies per year for the construction phase, i.e., 2004-2008, and the exploitation phase, i.e., 2008-2020. The figures are shown for a passive and active scenario. The passive scenario indicates the scenario where LOFAR is merely used for science. The active scenario indicates the scenario where LOFAR is exploited for non-scientific purposes as well.

Table 3.1. Expected employment effects of the LOFAR project (Bezemer and De Jong, 2003)

Scenario	**Passive scenario**		**Active scenario**	
Phase	**2004-2008**	**2008-2020**	**2004-2008**	**2008-2020**
Employment	**Jobs/year**	**Jobs/year**	**Jobs/year**	**Jobs/year**
Direct effects	155	90	155	90
Spinoff	34	30	45	80
ICT applications	21	106	266	1431
Care impact	126	136	279	961
Total number	336	362	745	2562

In addition, the knowledge created at ASTRON also stimulates R&D activities in Northern Netherlands. Besides a knowledge transfer to the academic community and business, the built-up knowledge also stimulates the initiation of new projects.

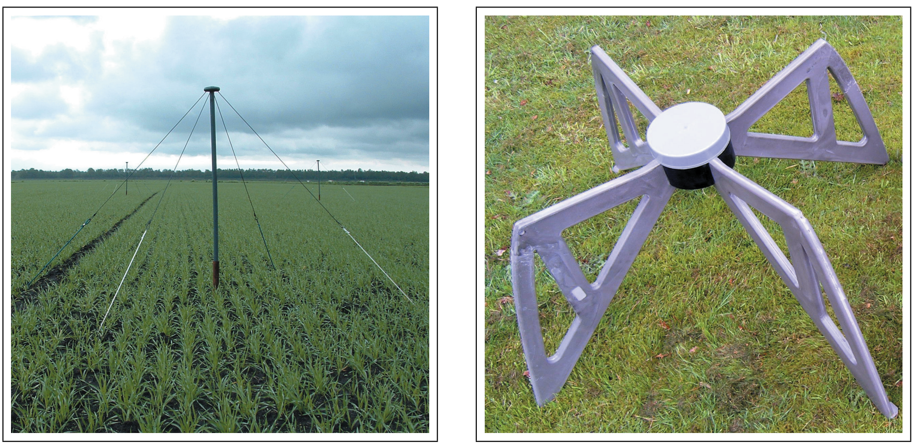
We also mention the effect of LOFAR as a training facility for academic students in astronomy and vocational college students in technology. The knowledge and experiences obtained in the training stage can be applied in a variety of job situations. This effect may yield a positive contribution to the Dutch 'knowledge economy'.

Finally, we address the economic relevance of ICT for the Netherlands. Expertgroep Breedband (2002a,b) states that 8% of the Dutch Gross National Product (GNP) is spent on ICT. According to the Netherlands Bureau for Economic Policy Analysis (CPB), 25% of the GNP growth results from the ICT sector and 50% of the productivity growth is directly related to ICT. Therefore, LOFAR may have a huge impact for the Dutch economy.

3.4 LOFAR Architecture

LOFAR is a radio array consisting of more than 100 antenna systems spread out in a large geographical area and connected by high-speed cables with a supercomputer that collects and processes the observed data. It is designed to explore the radio spectrum from 15 to 240 megahertz (Röttgering *et al.*, 2006). LOFAR is designed to use both earth rotation synthesis and multi-frequency synthesis (see Section 2.3.2) to maximize the imaging performance of the instrument (Noordam, 2001). The telescope is currently built in Northern Netherlands, but it will get extensions to the rest of the Netherlands and neighboring countries.

Each antenna system will be comprised of a large number of inexpensive receptor elements. We refer to antenna systems with such receptor elements as *sensor stations*. Each sensor station is equipped with 96 low frequency band and 96 high frequency band antennas. The low frequency band antennas are optimized for the frequency range 30-80 MHz; the high frequency band antennas are optimized for the frequency range 120-240 MHz (Gunst *et al.*, 2006). Figure 3.1 shows both types of antennas.



(a) Low frequency band antenna **(b)** High frequency band antenna

Figure 3.1. The receptor elements of the LOFAR telescope ©ASTRON

The sensor stations will be deployed in a *compact core area* with a diameter of two kilometers and in land parcels of about a couple of hectares in the *extended area*. Van Haarlem (2005) states that the collecting area should be laid out in an area with a diameter of about 400 kilometer. 25% of the collecting area should be located in the compact core area. The remaining collecting area should be distributed over three successive shells in the extended area. The distribution of the collecting area is given in Table 3.2.

Table 3.2. Distribution of the LOFAR collecting area

Location	Range	Distribution	Cum. distribution
Compact core area	$0 - 1$ km	25%	25%
First shell	$1 - 6$ km	25%	50%
Second shell	$6 - 37.5$ km	25%	75%
Third shell	$37.5 - \sim 200$ km	25%	100%

The collecting area should be laid out according to a *fractal structure* with an exponential scaling law (Bregman, 2000). A fractal structure is a structure which is *self-similar* at all scales, and is often described by a power-law. A self-similar structure is composed of parts that are (approximately) reduced-size copies of the whole structure. A fractal structure gives good zooming capabilities and has high flexibility with respect to the imaging performance of the instrument.

The LOFAR network should be scale free as well. A *scale-free network* is a network in which there are few nodes with high degree (i.e., hubs) and many nodes with low degree. This type of network is robust against random removals of nodes. The LOFAR network should exhibit the scale-free property within a sensor station and for the over-all array. An artist impression of part of the LOFAR network is shown in Figure 3.2.

Figure 3.2. Artist impression of part of the LOFAR network ©ASTRON

3.5 LOFAR Site Selection

Three sites have been proposed for LOFAR: the Netherlands (NL), the south-west USA (SWUS), and Western Australia (WA) (LOFAR SEC, 2003). We discuss the factors that have led to the final decision to build LOFAR in the Netherlands. This section is mainly based on LOFAR SEC (2003), Butcher *et al.* (2003), ATNF (2003), and Salah (2004).

3.5.1 Modern Factors in Telescope Site Selection

The atmospheric quality used to be the prime consideration in choosing a site for a ground-based telescope (Van den Bout, 2002). This holds in particular for optical telescopes, but also for radio telescopes. Modern radio telescopes usually operate at the lowest or highest part of the radio spectrum. These parts have limited terrestrial visibility due to atmospheric absorptions and the opaqueness and instability of the ionosphere (see Section 2.4.1). Since there are geographical differences in atmospheric transparency and stability, the atmospheric quality is also the prime consideration in the site selection process for radio telescopes.

Because of drastic technology improvements in recent years, it is now possible to deal with the poor quality of the atmosphere over many geographical sites. As a consequence, non-technical considerations receive more and more attention in the site selection process of radio telescopes and the atmospheric quality is no longer used as the prime consideration in choosing sites for radio telescopes.

On the contrary, RFI has become a crucial factor in the site selection process of radio telescopes. The RFI conditions at a site can seriously affect the performance of a telescope. Since mankind produces increasingly more radio noise, RFI levels get more and more attention while selecting sites for radio telescopes. Other considerations that can affect the site choice of a telescope are national interests, environmental concerns, operational considerations, investors' demands, personal preferences, and institutional or convenience considerations (Van den Bout, 2002).

3.5.2 LOFAR Site Selection Process

The LOFAR site selection process included a site evaluation and a selection process. The LOFAR Site Evaluation Committee (LOFAR SEC) was involved with the evaluation of the three sites based on scientific and technical criteria. The LOFAR International Steering Committee (LOFAR ISC) was charged with the site selection.

Evaluation Criteria

The LOFAR SEC has evaluated seven criteria for the proposed LOFAR sites. Weights have been assigned to each of them to indicate their relative priority. The seven criteria and corresponding weights used in the evaluation process are listed in Table 3.3. By assigning scores to each candidate site for each of the criteria, a relative ranking of the sites could be obtained against each single criterion and to all criteria.

Table 3.3. The LOFAR site evaluation process: criteria and weights (LOFAR SEC, 2003)

Criterion	**Weight**
1. Science	40%
2. Radio frequency interference	15%
3. Ionosphere conditions	15%
4. Physical characteristics	10%
5. Data connectivity	10%
6. Special characteristics	5%
7. Operational	5%
Total	*100%*

The highest weight has been assigned to the science goals of LOFAR (criterion 1). The science goals of LOFAR incorporate the LOFAR core objectives mentioned in Section 3.3.1 and the ionospheric science (ION). Because of the geographical locations, the scientific opportunities at the three LOFAR sites are different. Each LOFAR site has a unique sky coverage affecting the science goals that can be realized. Other site-dependent factors influencing the scientific opportunities are the local RFI environment, ionospheric conditions, and geographical constraints on the deployment of the sensor stations.

The technical feasibility of the array at the LOFAR sites depends on the RFI environment and the geographical conditions of the ionosphere. These factors (criteria 2 and 3) introduce complexity in design and uncertainty in performance. There is a potential risk that techniques to overcome this problem cannot be developed or are too expensive. These factors have been assigned the second highest weights in the evaluation process.

The design of the LOFAR telescope and its performance are also affected by the site's physical characteristics and data connectivity (criteria 4 and 5). The site's physical characteristics have to do with the accessibility of the site (e.g., flatness and vegetation), the land availability, and the local climate (e.g., rainfall, lightning, and temperature). The data connectivity has to do with the infrastructure at the site. The data collected by the sensor stations must be sent to a central processing facility. This factor is heavily influenced by the design of the telescope and the connectivity properties of the site. These factors are evaluated as slightly less important than RFI and the site's ionospheric conditions.

The lowest weights have been assigned to special characteristics and operational factors (criteria 6 and 7). The site's special characteristics include legal complications and environmental laws. They can slow down the construction process of the array and/or require additional costs to be made. The cost of local labor is also an example of a special characteristic. Operational factors are factors that have to be dealt with once the array is constructed. For instance, this category includes the overall robustness and reliability of LOFAR, the availability and cost of labor for system operations and maintenance, and parts availability.

Site Evaluation by the LOFAR SEC

The LOFAR Science Consortium Board (LOFAR SCB) was asked by the LOFAR SEC to evaluate the scientific opportunities at the three LOFAR sites. The three sites were ranked across the six LOFAR science categories (criterion 1 of Table 3.3) in a two-step ranking process. In the first step, the LOFAR sites were ranked on the basis of the scientific impact of the geographical location. In the second step, the non-geographical site-dependent factors were also incorporated in order to come to a final ranking. The results of the ranking process are given in Table 3.4. The table shows the relative ranking of the LOFAR sites for each of the six science categories (see Section 3.3).

Table 3.4. Ranking of LOFAR sites across science categories (Salah, 2004)

	Geography only			**Geography and other site-dependent factors**		
	1	2	3	1	2	3
EOR	SWUS	NL	WA	WA	SWUS	NL
EXG	SWUS	NL/WA		WA	SWUS	NL
GAL	WA	SWUS	NL	WA	SWUS	NL
TRANS	WA	SWUS	NL	WA	SWUS	NL
SOL	SWUS/WA	NL		SWUS/WA	NL	
ION	NL	WA	SWUS	SWUS	NL/WA	

Because the ranking in Table 3.4 is qualitative, a quantitative assessment was carried out in order to determine the strength of the ranking across science categories. By means of discussions and a questionnaire, the LOFAR sites were quantitatively assessed for each science category. The results were then converted to rank the LOFAR sites numerically using the *Analytic Hierarchy Process* (AHP). AHP is a decision-making framework to deal with complex problems (Saaty, 1980). Table 3.5 gives the normalized AHP ranking with the non-geographical site-dependent factors included and the science categories equally treated.

Table 3.5. AHP ranking of LOFAR sites on science criteria (Salah, 2004)

Science area	**Weight**	**NL**	**SWUS**	**WA**
EOR	$\frac{1}{6}$	20	35	45
EXG	$\frac{1}{6}$	23	35	42
GAL	$\frac{1}{6}$	8	21	71
TRANS	$\frac{1}{6}$	13	31	56
SOL	$\frac{1}{6}$	18	41	41
ION	$\frac{1}{6}$	31	36	33
ALL		19	33	48

In the geography-only based consideration, both the southwest USA and Western Australia outperform the Netherlands. When the non-geographical site-dependent RFI factor is incorporated, the AHP ranking of Table 3.5 shows that Western Australia is the best site to perform scientific research. Therefore, the LOFAR SEC established the following site ranking: 1. WA, 2. SWUS, and 3. NL.

The figures in Table 3.5 give strong motivation to build LOFAR in Western Australia. However, when the figures would be different, one may argue the performed AHP ranking process. First, it is likely that certain science categories are more important than other ones. Thus, the assumption of equal weights is questionable. Second, it is not clear how the site scores are determined. One may require a minimum performance for the science categories at each site or penalize low scores more than higher ones.

The RFI levels at the three LOFAR sites were determined by the site hosts (criterion 2 of Table 3.3). Engineering experts reviewed and commented on the RFI reports. They concluded that Western Australia is superior to both the Netherlands and the southwest USA, but that RFI levels will vary within the sites for the array. Some experts expressed their concern about the high RFI levels in the Netherlands and southwest USA which would require expensive counter measures. The RFI reports were compiled and evaluated by the LOFAR SEC. The LOFAR SEC shared the same opinion as the engineering experts and were aware of the fact that costly *mitigation schemes* (see glossary, p. 259) are indispensable in both the Netherlands and the southwest USA.

Ionospheric studies were performed by the LOFAR SEC to determine the ionospheric irregularities at the LOFAR sites (criterion 3 of Table 3.3). Many patch-like irregularities were found, but they were mainly caused by a *sunspot maximum* (see glossary, p. 259). After accounting for the solar cycle effect, the overall levels of ionospheric fluctuations were acceptable for all the sites. No significant differences in the behavior of the ionosphere at the sites could be observed as well.

The physical characteristics of the LOFAR sites were also not distinguishing between sites (criterion 4 of Table 3.3). Although the sites differ with respect to land availability, water bodies, urbanized areas, and rugged terrain, none of them rule out any site. Therefore, the LOFAR SEC concluded that all three sites are capable of deploying LOFAR.

The LOFAR data connectivity deals with the data transport within the array and to users spread across the world (criterion 5 of Table 3.3). The sensor stations in the inner region should be linked up with dedicated fiber and they should be kept in own managerial control. The sensor stations in the outer region are allowed to be connected with existing fiber. In addition, the LOFAR network should be linked up to high-speed communication networks to allow researchers all over the world to have access to the instrument's data. Table 3.6 represents the data connectivity characteristics at the three LOFAR sites.

The LOFAR SEC has also reviewed the special site characteristics and the operational factors (criterion 6 and 7 of Table 3.3). They concluded that land availability, legal considerations, indigenous people, environmental impact issues, and labor costs were not expected to cause major problems at any of the sites. Nor was it expected that operational requirements would have major advantages or disadvantages at any of the sites.

Table 3.6. Data connectivity characteristics of the LOFAR sites (LOFAR SEC, 2003)

Site	Compact core area	Extended area	Internet access
NL	Dedicated fiber - laid by the project. Sharing with other sensor arrays is possible, but limited with respect to non-science applications.	Dedicated fiber - laid by the project where needed. Using existing infrastructure where possible.	Link to national academic network guaranteed and possible to international networks via academic networks. Additional connections to the US east coast being explored.
SWUS	Dedicated fiber - laid by the project and existing fibers. Shared use being considered for connecting the compact core with the rest of the inner array.	Extensive use of existing fiber.	Link to Internet2 network possible, yielding Gbit connections.
WA	Dedicated fiber - laid by the project. No sharing with other users.	Dedicated fiber - laid by the project. No or limited sharing with other users.	Link to national and international networks with Gbit connections possible.

Western Australia is dominant for all seven criteria. It is ranked the highest on all science categories except ionospheric science (criterion 1). It is also ranked highest with respect to RFI levels (criterion 2). No definite ranking can be found for any of the other factors (criteria 3-7). Therefore, the LOFAR SEC has evaluated Western Australia as the best site for building LOFAR.

Site Selection by the LOFAR ISC

The LOFAR ISC reviewed the evaluation report submitted by the LOFAR SEC. They endorsed that innovative research can be conducted at all the sites, but that the Netherlands and the southwest USA have high RFI levels which impose risks to realize the science goals of LOFAR and to construction costs. The LOFAR ISC also considered the financial contributions of the site hosts. All site hosts were willing to provide site development and to supply financial resources. The financial plan offered by Australia was perceived as most acceptable. On September 6, 2003, the LOFAR ISC signed a joint statement establishing that Western Australia site is the optimal site for LOFAR.

LOFAR in the Netherlands

Once the optimum LOFAR site had been determined, the LOFAR ISC initiated discussions and negotiations with the Australia Telescope National Facility (ATNF) and the Government of Western Australia on the proposed siting of LOFAR. At the same time a consultation process was started to measure the level of interest of the Australian astronomical community for the science areas to be addressed by LOFAR. In December 2003, the National Committee for Astronomy in Australia agreed upon the recommendations of the Australian LOFAR working group that Australia should try to join the LOFAR consortium conditionally. In particular, LOFAR should be sited in Western Australia and LOFAR should facilitate the long-term Australian astronomy goals, including the Square Kilometre Array.

In November 2003, however, the Dutch government had already decided on a funding of €52 million for the development of LOFAR in the Netherlands. This funding was linked to the infrastructure development in the Netherlands. ASTRON received this funding on the condition that it would be the launching customer of the new infrastructure. In early 2004 it became clear to the ATNF that ASTRON funds could not be used for an international project in Western Australia and that new funds were not available. Therefore, the ATNF decided not to proceed with the LOFAR project, and the project moved to the Netherlands. For more background information on the LOFAR site selection, see Hogan (2006).

The LOFAR site selection process illustrates that political and financial considerations are very important in telescope site selection. Modern telescopes are often wide-area radio arrays involving large sums of financial resources. Since these telescopes also have a socio-economic impact funding issues often have a political foundation. They can overrule the outcome of a site selection process which is merely based on scientific and technical criteria.